HYPERLOOP ACCELERATOR

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Abstract

The hyper loop is a conceptual super-fast fifth mode of transportation, the designs for which have been put forth by Elon musk, the CEO of Tesla Motors & SpaceX. The designs have been made public for anyone to view and improve upon as musk hopes this to be an open-source project. The main concept of hyper loop involves the movement of an aerodynamic capsule through partial vacuum tubes

Since, Spring 2013, the Department of Mechanical Engineering at the University of Illinois, has been working to create a proof of concept prototype of the hyper loop. The prototype consists of a loop of partial vacuum tubing and aims to launch a small capsule around it. The goal of our project is to build a linear accelerator in the form a multi-stage coil gun in order to impart enough momentum to a capsule to move around the loop continuously without reset

Contents

1. Introduction

The scope of the project can be divided into three main parts:

1) Coil Magnetic Theory: In order to determine the magnetic force experienced by the capsule and energy transfer from coil to capsule it was important to develop a basic theoretical understanding of the electromagnetics of a finite solenoid

2) AC/DC Convertor: This is required to provide a current impulse to the coil using a circuit consisting of resistors, a capacitor and a bridge circuit. The circuit essentially converts AC supply from a wall plug into steady stated DC to be supplied to coil.

3) Controls: For developing the multiple stages, a control system is required consisting of sensors and an arduino that is able to sense the approaching capsule and turn the coil on before the capsule reaches to provide further acceleration.

1.1 Block Diagram

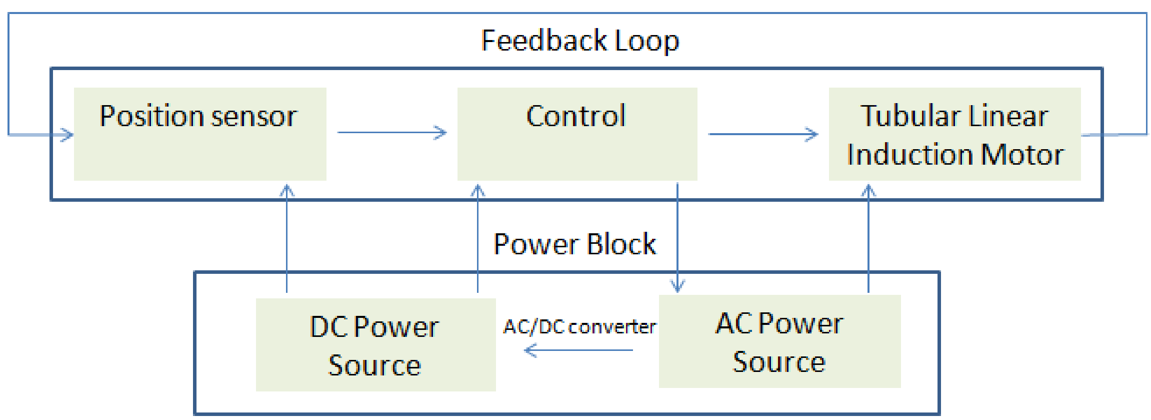

Figure 1. Block Diagram for project

2 Design

2.1 General Description

Consider a multistage coil gun setup with n coils. Each coil has a sensor placed in front of it. The sensor, on detecting the iron capsule sends a signal to the arduino control circuit. The controls turn on the thyristor switches and discharge the capacitor in the AC/DC convertor which is fed with a 240 V source. The capacitor provides a current pulse to the coil magnetizing it hence applying a force on the iron capsule giving it momentum.

2.2 Power & Control Circuitry

The circuit schematic for controls and power is given below with a description of the operation of each part of the circuit.

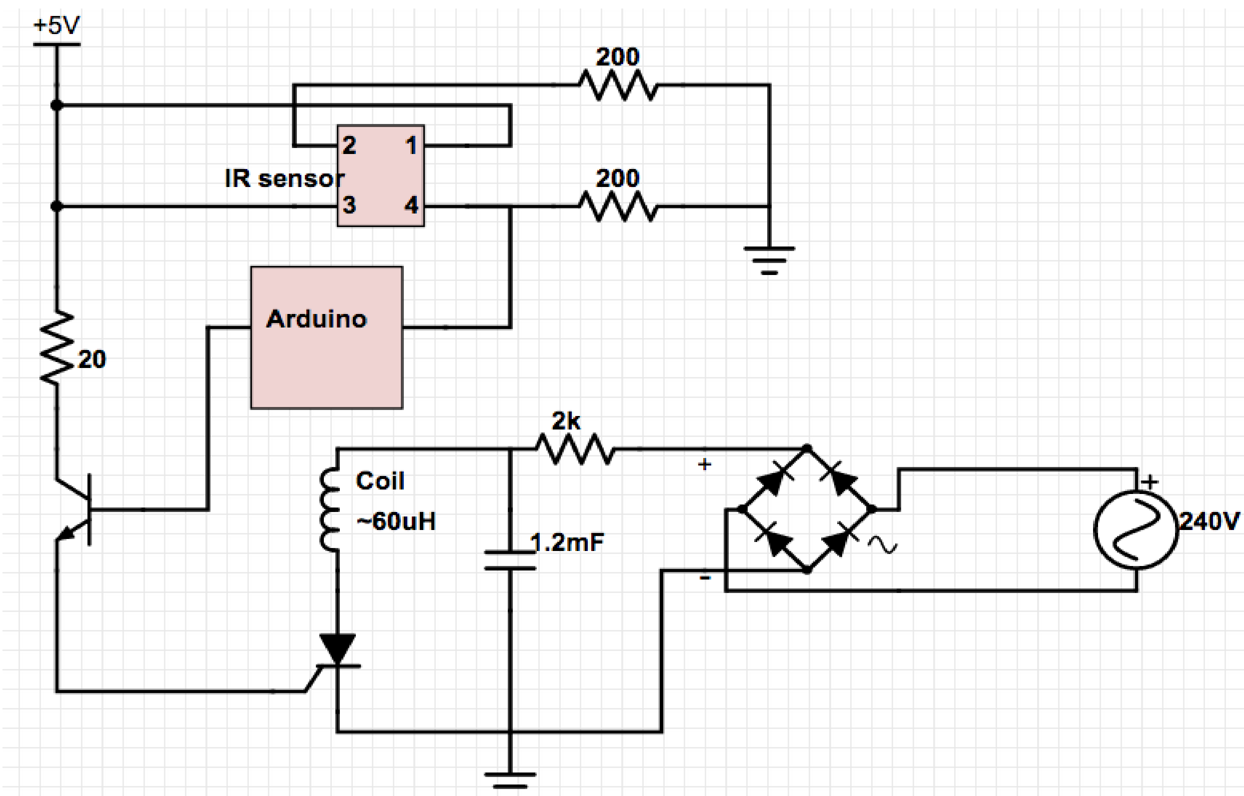

Figure 2. Control & Power schematic

2.2.1 Power Circuitry

The premise of our charging circuit is that 240 VRMS needs to be converted into 260 VDC in order to charge a Capacitor. Once the capacitor is charged, one can use the control circuit to discharge the capacitor through the coil to generate a pulse.

A 240 VRMS wall power input goes through a bridge rectifier that takes the absolute value of the input voltage. The output of the rectifier goes through a 2kΩ 50W power resistor to the 1.2 µF capacitor to charge the capacitor when the bridge rectifier voltage is higher than the capacitor voltage, and slowly discharge the capacitor for the brief period when the bridge rectifier voltage is lower than the capacitor voltage.

While this method for charging a capacitor is crude, our requirements for the coil only need the capacitor voltage to reach 260V within 10 seconds. For designing purposes we will engineer 4 time constants within 10 seconds to allow for recharging. We chose to use a 2kΩ resistor with the 1.2 µF capacitor that created a time constant of 2.4 seconds. Thus we estimated it would take 9.6 seconds to charge the capacitor (it actually took 8 seconds).

2.2.2 Control Circuitry

An Arduino Uno is used to measure the intensity of the input from an IR sensor. The Arduino is necessary because each sensor has different sensitivities to reflected IR light. That causes the threshold signal to differ for each sensor and requires us to use the Arduino to calibrate the output of each sensor for use in our design.

Once the sensors tell the Arduino to fire a coil, the Arduino provides a small base current to an NPN common emitter circuit. The common emitter circuit amplifies the Arduino signal and provides at least 100mA to a thyristor in order to activate the firing of the coil. Without the thyristor the Arduino would burn out since it can only provide up to 40 mA.

One last note on the control circuit is that we used a 9V battery as a supply to the Arduino, the sensors, and the thyristor base current. For future work we will use a down-transformer to build the 9V source into the circuit.

2.3 Electromagnetic Theory & Coil Design

2.3.1 Introduction

The basic electromagnetic theory involved in the operation of a coil gun is as follows.

Consider a circular coil of winding with "N" turns. When we pass a current ("I") through the coil, given ampere's law, magnetic flux ("φ") is established in the area encompassed by the coil. This magnetic field is strongest at the center of the coil and decreases axially. The coil is now essentially a temporary magnet with the north pole at the face through which magnetic flux lines come out and the other face the south pole.

A ferromagnetic material in the vicinity of the coil (temporary magnet) will get magnetized. The surface of the material facing a particular pole of the coil is magnetized as an opposite pole. Magnetic dipoles within the ferromagnetic material will align themselves so that the material is attracted to the magnetic field. In this way the ferromagnetic cylinder will experience an attractive force due to the magnetic field and get accelerated towards the coil. In a multi-stage coil, coils are placed next to each other and once the cylinder has passed completely through one coil, the current through it is turned off (if the current remained on then once the ferromagnetic material was on the other side it would experience attractive force in the direction it just came from) and the current in the coil next to it is turned on. This way the ferromagnetic material continues to experience attractive forces in the same direction and can be linearly accelerated.

2.3.2 Equation for Magnetic Field Intensity and Force for a single coil

The first step towards building the coil gun required us to establish a model to study the magnetic field produced by the coil and the magnetic force experienced by the capsule. After consulting with the mechanical engineering team it was decided that a linear model for magnetic field obtained from a research paper [1] would be used. The linear model is described below

This section uses a linear model to approximate the magnetic field intensity (H) and magnetic force (F) at a point 'p', some distance x from the coil with N turns. H and F are then plotted as a function of distance.

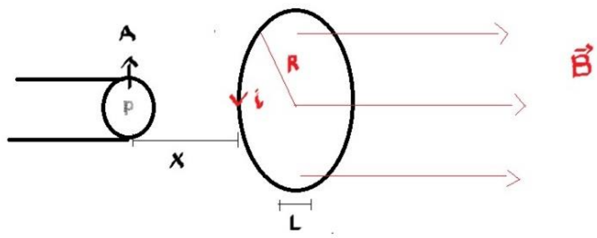

Figure 3. Interaction between a coil winding and cylindrical iron core

Magnetic Field Intensity and Force for a single coil

Consider the diagram above, with a coil and solid iron cylinder.
i = Current through the coil
N = number of turns
L= length of winding
R = Radius of the coil
A = Area of the face of the iron cylinder
Consistent with Ampere's Law. The magnetic flux density (B) through a coil with current (i) flowing in it is maximum at the center of the coil and decreases axially.

The magnetic field intensity H is given by :

$$H = \frac{B}{\mu_0} \tag{1}$$

μ_0=permeability of free air

At the center of the coil,

$$B(x = 0) = \frac{u_0 I}{2R} \tag{2}$$

The axial field is much more complicated to calculate. Referring to a research paper [4]that adopts a linear model for calculating H, the axial magnetic field intensity can be approximated by the following formula,

$$\mathbf{H}(\mathbf{x}) = \frac{nI}{2}\left(\frac{L-x}{\sqrt{(L-x)^2+R^2}} + \frac{x}{\sqrt{x^2+R^2}}\right)\hat{x} \quad (3)$$

As seen above, the axial field is a function of distance (x) and is maximum at the center of the coil.

The force experienced by a ferromagnetic material interacting with this field can then be approximated by the following formula:

$$F(x) = \mu_0 A \chi_x (H(x)^2 - H(x-l)^2) \quad (4)$$

Where, X_{x} = linear magnetic susceptibility as function of x.
These equations are too complex to solve for H or F. Plotting these equation within a particular interval for x gives us a good idea of what H and F look like as the position of the iron cylinder changes with respect to the coil.

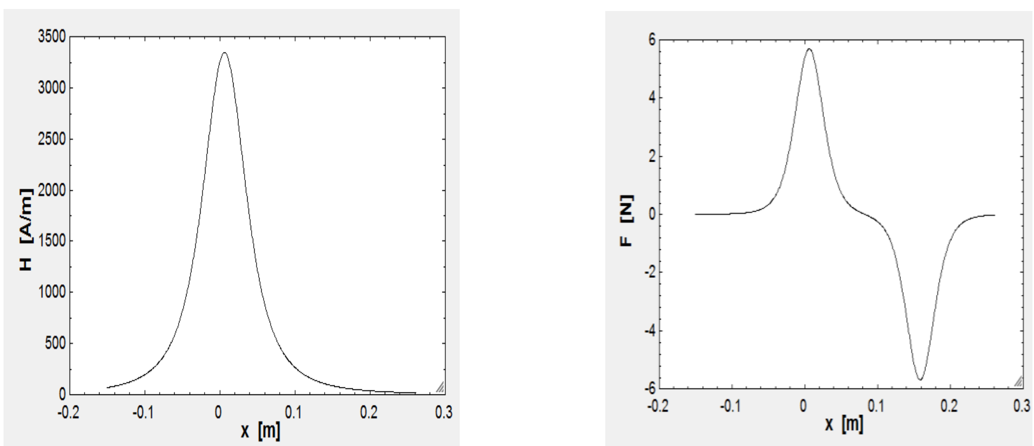

Figure 4.

4.1. Magnetic Field Intensity vs Position

4.2 Magnetic Force on cylinder vs position

Taking x=0 for as center of the coil. As mentioned in the introduction the field intensity is maximum at the center of the coil and decreases axially. Also, the direction of force reverses once the cylinder crosses the center of the coil.

<u>Conclusion</u>: The coil must be turned off before the cylinder reaches the center of the coil and the next coil in the multi-stage coil gun must be turned on to continue the acceleration process which is consistent with our initial understanding.

2.3.3 Important coil parameters

The following are the parameters of the coil gun system that crucially define its function:

- Coil Radius: "R" (this is the radius of the coil + the thickness of the PVC pipe (hyperloop tubing) it is wrapped around)
- Coil Length: "c"
- Coil # Turns: "N"
- Coil Inductance: "L"
- Capsule Radius: "r"
- Capsule Length: "l"
- Capsule Material Permeability: "µ"
- Minimum distance the capsule must be placed from the center of the coil to experience maximum force: "x"
- Distance between coils for the multi-stage: "y"

Since we took over the project from a previous team, certain parameters of the coil gun were fixed from the beginning and we had to work within those constraints:

R=4.125cm
N=300
c=1.3 cm
r=2.475cm (because the hyperloop concept requires that the radius of the capsule be 60% of the radius of the tubing)
y= n*(0.5 inches) {where n is an integer} [This is because the Mechanical Engineering team has wood/aluminum casing apparatus to mount the coils onto the PVC pipe with slots for each coil. The distance between each slot is 0.5"]

Figure 5. Apparatus to set coils on PVC pipe

The remaining parameters needed to be determined.

It is important to mention at this point the **limitations of the linear theoretical** model used to estimate the field to the coil. The linear model fails to take into account the radial fields due to the coil, which add to the magnetic field. The linear model also fails to take into account flux linkage (that is how much of the field produced interacts with the capsule). This is important because our set up has a big air gap

between the coil and the capsule. Thus, there isn't 100% energy transfer from the coil to capsule. It is important to know how much energy is lost in the air gap to truly determine the force and velocity gained by the capsule. Since flux linkage is associated with the dimensions of the iron capsule, the first step was to estimate an ideal length "l" for the capsule. In order to determine optimal "l", we first tried to manipulate the Force Equation (4). However, the results obtained were unsatisfactory. This, I believe, was due to the limitation of the linear theoretical model mentioned above. At that point, ww decided to try to solve the problem empirically through testing. In order to determine the optimal length, we decided to manipulate the relationship between the inductance of coil and its parameters.

2.3.4 Determining optimal length of capsule

In order to determine optimal length, first we need to look at the relationship among the current through the coil (I) , the flux through the coil (ϕ) and the inductance of the coil (L), given by

$$\varphi = L/I \tag{9}$$

Now, consider a coil with an air core. Its inductance is given by :

$$L_{air} = u_0 N^2 A/c \tag{10}$$

Now consider an iron core with area of cross-section and length same as that of the coil. Its Inductance is given by

$$L_{iron} = \frac{u_m N^2 A}{l} \tag{11}$$

Where, u_m is the permeability of the iron core.

From (10), it is evident that the inductance of the coil is inversely proportional to its length. From (9), we see that the flux through the coil is proportional to L for a fixed I. I is determined by our bridge circuit and is fixed. From (11), we also see that the inductance of a coil with an iron core inside it, is maximum when the iron completely occupies the volume inside the coil. Thus, the flux through the coil will also be maximum for that case. Hence, the force experienced by the capsule will also be maximum. It is safe to assume at this point the optimal length of the capsule should be equal to that of the coil. Further evidence is provided for this when we consider reluctance of an iron core. Reluctance (R) in magnetic circuits is akin to resistance in electrical circuits. The Reluctance of an iron core is defined as its opposition to establish flux in the core as is given by

$$R = \frac{l}{\mu_m * A} \tag{12}$$

Hence, in order to have maximum flux through the core its length should be as small as possible. Thus, l=c is a good estimate to take. Since, the radius of the core is fixed, smallest possible l will also minimize its weight and hence air friction during its motion.

Further, tests were conducted to affirm this approximation and are described in the verifications section.

3. Design Verification

The parts to verify fall into two categories: circuit functionality, and desired physical properties.

3.1 Circuit Functionality

3.1.1 Capsule Kinetics

To ensure the motor can sufficiently accelerate the capsule, we placed a barrier 20cm downstream from the coils. When fired, the capsule was able to consistently hit the barrier. In addition, we were able to engineer the system to not need a reset button, which is a requirement for automatically re-firing. We passed two capsules through the coil and both were accelerated to hit the barrier.

3.1.2 Sensitivity of Sensors

Each IR sensor was unique in that some we more sensitive to reflected light than others. While all sensors provided a baseline voltage of 0.8V-1V, when the capsule passed over the sensor the voltage would go from 1.2V-3V. As such we set a threshold voltage of 1.1V to fire the capsule. We also programmed an LED light to turn on whenever a sensor detected the capsule. We used this LED for demonstration purposes and it operated as expected.

3.1.3 Power Source

When fired, the capacitors used to generate the pulse need to recharge faster than the time it would take for the capsule to make it around the loop. We estimated this time would be 10 seconds. While we designed the recharging to be finished in 9.6 seconds, we were pleasantly surprised when it only took 8 seconds to recharge to 210 VDC. We used an iPhone as a timer and a voltmeter to measure the DC voltage.

3.1.4 Thyristor Activation

To ensure that the Thyristors turns on to activate the coil current we needed to supply at least 100mA to the base of the Thyristor. Because we are using a common emitter setup, we can measure the current through the 20 Ω resistor as a measure of the thyristor base current. When the Arduino output to the common emitter base was 5V the 20 Ω resistor current was 166 mA which is more than enough to turn on the thyristor. When attached to the coil, the thyristor consistently fired the coil as expected.

3.2 Testing to verify optimal capsule length

The circuit in figure 2 was used without the control circuit to test a coil with iron capsule of length 0.5 inches (equal to that of the coil). A source voltage of 220V charged up the capacitor to 340V providing 60J of energy.The capsule was placed at distance 1.5 inches, 1 inch and 0.5 inch from the center of the coil and the following results were obtained:

X (distance from center of the coil)	Observation on iron capsule
1.5 inch	No Movement
1 inch	Barely any motion
<=0.5 inch	Capsule rolled out of the other end of the coil

Therefore our theoretical affirmation was realized.

Also, x was determined to be <=0.5

3.3 Test to determine coil inductance

The relationship between a coil's inductance and its parameters is as described below:

$$L = u_0 N^2 A/c \tag{5}$$

Where u_0 = permeability of free air

A = area of cross-section of the coil.

The theoretical value of inductance was found to be L= 6.053 mH. It was important that this value was verified through experimental testing.

The following experiment[2] was conducted to verify the inductance value:

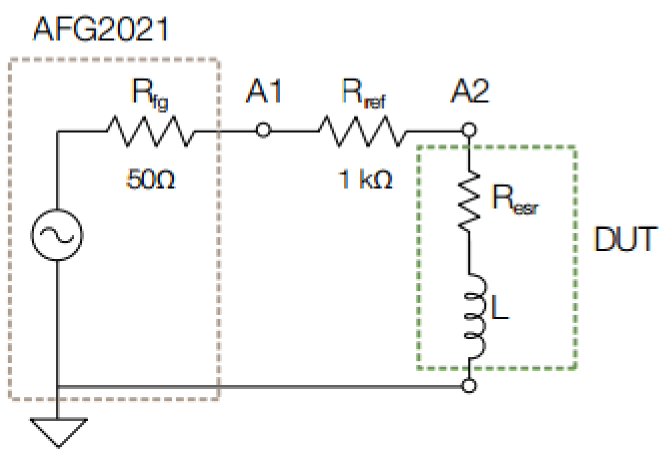

Figure 5. Circuit to determine Inductance

A function generator is used to supply a sinusoidal signal at V_{pp}= 1.9V and frequency 10kHz to the circuit. The circuit is probed at A_1 and A_2 to obtain voltages (V_{A1} & V_{A2}) and phase difference (Θ) between the voltages.

The following equations are then used to determine L:

$$Z = V_{A2}R_{ref} \Big/ \sqrt{V_{A1}^2 - 2V_{A1}V_{A2}COS(\Theta) + V_{A2}^2} \tag{6}$$

$$\alpha = \Theta - \tan^{-1}\left(-\frac{V_{A2}sin\Theta}{(V_{A1} - V_{A2}cos\Theta)}\right) \tag{7}$$

$$L = \frac{Zsin\alpha}{2\pi f} \tag{8}$$

It was found that V_{A1} = 3.83V, V_{A2} = 1.348 V, Θ=67 degrees. This gave L = 6.075 ohms, verifying our theoretical calculation

4 COST AND SCHEDULE

4.1 Cost Analysis

4.1.1 Labor Cost

Name	Hourly Rate	Total Hours Invested	Total labor Cost = Hourly Rate x 2.5 x Total Hours Invested
Mohammad Jaber	$30	160	$12000
Michael Eraci	$30	160	$12000
Shivam Sharma	$30	160	$12000
Total			**$ 36,000**

4.1.2 Parts

Item	Quantity	Cost
Additional copper wire	10m (approx)	$5
Bridge Rectifier	1	$2.85
9V battery	2	$10
IR sensors	4	$5
PCB board	1	$10
9V battery clips	2	$0.78
Capacitor	3	$34.48
Thyristors	12	$24.9
Arduino Board	1	$20
Connecting wires	20-30	$15

TTL Chips	5	$10
Total		**$138.01**

* Since the motor is already partially assembled we will mostly be working with the parts at our disposal.

4.1.3 Total Cost

Section	**Total**
Labor	**$36,000**
Parts	**$138.01**
Total	**$36,138.01**

5. Conclusion

5.1 Accomplishments

We successfully demoed a two stage coil gun. The two coils imparted momentum to a two inch piece of iron and move it approximately 0.2m. The sensor and controls allowed for continuous operation of coil gun without having to reset the 240V source.

5.2 Uncertainties

The logic component of our circuit is powered through a 9V lithium battery. Since, these batteries have limited life, they will need to be replaced at some point in the future.

5.3 Future work

Future work involves building the control and AC to DC convertor circuits for 18 coils, in order to get the capsule to navigate the entire loop of tubing.

Work also needs to be done to impart power to the control circuit through the 240V source instead of the 9V battery.

References

[1] Jeff Holzgrafe, Nathan Lintz, Nick Eyre, & Jay Patterson, Effect of Projectile Design on Coil Gun Performance ,Franklin W. Olin College of Engineering, December 14, 2012;

http://www.nickeyre.com/images/coilgun.pdf

[2] Tektronix manual. Attached as a separate file in the e-mail

[3] Thyristor (BT 139-600) datasheet
http://www.farnell.com/datasheets/1758085.pdf

[4] Bridge Rectifier (583-MP154) datasheet
http://www.mouser.com/ds/2/345/mp1505-1510-14294.pdf

[5] Capacitor (667-EET-HC2E1220A) datasheet
http://www.farnell.com/datasheets/1758085.pdf

Appendix A Requirement and Verification Table

Requirement	Verification	Points
1. Induction Motor: a. The motor can make the capsule move at least the length of the motor, which is 0.2 meters. b. The motor can power continuous movement of the capsule though the tube without the need to turn off and on again or provide an outside force on the capsule.	a. Measure the distance traveled with a measuring tape. b. After accelerating the capsule through the loop, insert the capsule again and confirm that the capsule is accelerated a second time.	**40** **10**
2. Sensors: a. Each coil of winding has a sensor associated with it. The sensor detects presence of the capsule and sends information to the control system. The control system then turns off present coil and turns on the next one.	a. When the capsule is directly under each sensor an output LED from the microcontroller turns on and when the capsule is not the LED output turns off.	**20**

3. The Power Source: a. An RC circuit will convert 240 VRMS AC current to 300 VDC +/- 40 VDC used to power the coil gun in 6 seconds +/- 4 seconds.	a. An oscilloscope trace of the capacitor voltage will show the capacitor voltage 2 second after and 10 seconds after the pulse signal is activated. The voltage after 2 seconds must be less than 260 VDC. b. The voltage after 10 seconds must be between 260 VDC and 340 VDC.	**10** **10**
4. Thyristor Switching a. Our thyristors require 100 mA to turn on. An Arduino Uno and a NPN transistor will supply 175 mA +/- 75 mA to a thyristor (not trivial since at most 40 mA can come from the Arduino Uno).	a. Use oscilloscope to measure the peak voltage across a 20 Ohm resistor from one second before and one second after a pulse and verify that the peak voltage is between 3.5V and 5V.	**10**

Appendix B Arduino Code

```
void setup () {
  pinMode(2, OUTPUT);
  pinMode(3, OUTPUT);
  pinMode(4, OUTPUT);
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(13, OUTPUT);
  Serial.begin(9600);
}
void loop() {
  int pulseDuration=50;
  int threshold=100;

  int val0=analogRead(A0);
  int val1=analogRead(A1);
  int val2=analogRead(A2);
  int val3=analogRead(A3);
  int val4=analogRead(A4);
  int val5=analogRead(A5);
//  Serial.println(val0);
//  Serial.println(val1);
//  Serial.println(val2);
//  Serial.println(val3);
```

```
//  Serial.println(val4);
//  Serial.println(val5);
  if(val5 >threshold)
  {
    digitalWrite (7, HIGH);
    digitalWrite (13, HIGH);
    delay(50);
    goto LEDLIGHTING;
  }
  else
  {
    digitalWrite (7, LOW);
  }
  if(val4 >threshold)
  {
    digitalWrite (6, HIGH);
    digitalWrite (13, HIGH);
    delay(50);
    goto LEDLIGHTING;
  }
  else
  {
    digitalWrite (6, LOW);
  }
  if(val3 >threshold)
```

```
{
   digitalWrite (5, HIGH);
   digitalWrite (13, HIGH);
   delay(50);
   goto LEDLIGHTING;
}
else
{
   digitalWrite (5, LOW);
}
if(val2 >200)//thumb triger threshold
{
   digitalWrite (4, HIGH);
   digitalWrite (13, HIGH);
   delay(50);
   goto LEDLIGHTING;
}
else
{
   digitalWrite (4, LOW);
}
if(val1 >threshold)
{
   digitalWrite (3, HIGH);
   digitalWrite (13, HIGH);
```

```
    delay(50);
    goto LEDLIGHTING;
  }
  else
  {
    digitalWrite (3, LOW);
  }
  if(val0 >200)//thumb triger threshold
  {
    digitalWrite (2, HIGH);
    digitalWrite (13, HIGH);
    delay(50);
    goto LEDLIGHTING;
  }
  else
  {
    digitalWrite (2, LOW);
  }
  LEDLIGHTING:
  if(!(val0>200||val1 >threshold||val2 >threshold||val3 >threshold||val4 >threshold||val5 >threshold))
     digitalWrite (13, LOW);
}
```